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Magnetic confinement, magnetohydrodynamic waves and smooth line profiles in active galactic nuclei

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ABSTRACT

In this paper, we show that if the broad-line region clouds are in approximate energy equipartition between the magnetic field and gravity, as hypothesized by Rees, there will be a significant effect on the shape and smoothness of broad emission-line profiles in active galactic nuclei. Linewidths of contributing clouds or flow elements are much wider than their thermal widths, because of the presence of non-dissipative magnetohydrodynamic waves and their collective contribution produce emission-line profiles broader and smoother than would be expected if a magnetic field were not present. As an illustration, a simple model of isotropically emitting clouds, normally distributed in velocity, is used to show that smoothness can be achieved for less than $\sim 8 \times 10^4$ clouds and may even be as low as a few hundred. We conclude that magnetic confinement has far-reaching consequences for observing and modelling active galactic nuclei.

Key words: line: profiles – magnetic fields – MHD – galaxies: active – galaxies: nuclei.

1 INTRODUCTION

Quasar emission lines are important probes of the physics of active galactic nuclei (AGN). The primary assumption made in spectra-line synthesis studies of AGN is that the width of a component contributing to the total line profile is thermal. The assumption is made regardless of whether the component is a single cloud in a discrete ensemble of clouds or a differential volume element in a continuous flow.

Line emission originates in matter at $\sim 10^4$ K and corresponds to a thermal width of ~ 10 km s⁻¹. Since broad-line region (BLR) emission lines have much larger widths (FWHM $\sim 10^3$ to $\sim 10^4$ km s⁻¹) the width of an individual component is often assumed to be negligible compared with the total line profile. Based on this assumption and the observed smoothness of broad emission-line profiles, cloud numbers in excess of 10^7 to 10^8 are inferred (Arav et al. 1997; Arav et al. 1998; Dietrich et al. 1999).

This need not be the case, however. If a magnetic field is present, the linewidth of a contributing element will be broadened requiring fewer clouds to produce the observed profile smoothness.

In nature a magnetic field is usually associated with non-dissipative magnetohydrodynamic (MHD) waves in energy equipartition with the magnetic field. Thus

$$\frac{B^2}{8\pi} \approx \frac{1}{2} \rho \sigma_B^2 \quad (1)$$

where $B^2/8\pi$ and $1/2\rho\sigma_B^2$ are the magnetic pressure and MHD wave-energy density respectively, ρ is the mass density and σ_B is the resulting velocity width of the gas (Arons & Max 1974; Myers & Goodman 1988a; Myers & Goodman 1988b).

Rees (1987) suggested that BLR clouds are magnetically confined. Assuming

$$\frac{B^2}{8\pi} \geq nkT \quad (2)$$

and solving for B gives

$$B \geq \sqrt{8\pi nkT} \sim 0.6 \sqrt{n_{10} T_4} \text{ G} \quad (3)$$

where n_{10} is the density in units of 10^{10} cm⁻³ and T_4 is the temperature in units of 10^4 K. From this we see that only a few Gauss are required for confinement. Substitution of equation (3) into equation (1) and solving for σ_B gives a lower bound for the line width of magnetically confined BLR gas. Thus

$$\sigma_B \geq \frac{B}{\sqrt{4\pi\rho}} \approx \sqrt{\frac{2kT}{m_A Z}} \approx 11 \sqrt{T_4} \text{ km s}^{-1} \quad (4)$$

where m_A is one atomic mass unit and Z is the mean atomic weight of the gas which, assuming cosmic abundances, is taken to be $Z \approx 1.4$. This is comparable with the thermal width of hydrogen, but is roughly 3.5 times larger than the thermal width of carbon (~ 3.2 km s⁻¹), and 7.5 times larger than the thermal width of iron (~ 1.5 km s⁻¹) at $T_4 \approx 1.0$. Thus, even for the minimal confining magnetic field there will be significant effects on line transfer.

The broadening is considerably amplified, however, if the magnetic field is in equipartition with the gravitational energy density so that

$$\frac{B^2}{8\pi} \approx \frac{GM\rho}{R} \quad (5)$$

(Blandford & Payne 1982; Rees 1987; Emmering, Blandford & Shlosman 1992; Königl & Kartje 1994; Bottorff et al. 1997). Although there is no fundamental reason why equation (5) should hold, this equipartition does occur in many environments (Rees 1987; Meyers & Goodman 1988a,b). Here R is the radial distance of gas, with mass density ρ , from a central black hole of mass M . In this case, the line width will be greater than the virial width, the local velocity field will be highly supersonic and MHD broadening may actually account for the full width of an emission line.

2 A SIMPLE MODEL

To illustrate the effect of non-dissipative MHD wave line broadening and smoothing on an emission-line profile, we consider the extreme case of BLR emission arising from a discrete set of identical clouds. This example has immediate applicability in the search for discrete clouds or extended cloud structures in BLR line profiles (Arav et al. 1997; Arav et al. 1998; Dietrich et al. 1999).

2.1 A discrete distribution of emitters

A simple one-dimensional outflow model is constructed in which clouds move only along the line of sight. We choose a cloud bulk velocity field given by

$$v_G \approx \sqrt{\frac{2GM}{R}}. \quad (6)$$

Requiring consistency with equation (1) and equation (5) gives

$$\sigma_B \approx \sqrt{\frac{B^2}{4\pi\rho}} \approx \sqrt{\frac{2GM}{R}} \approx v_G. \quad (7)$$

Thus the dispersion of an emitting element equals the systemic velocity at any given radius. (Note: A magnetic example in which $v_G \sim \sqrt{2GM/R}$ is the MHD wind model of Blandford & Payne (1982). In that paper v_G is also given by $v_G \sim \sqrt{B^2/4\pi\rho}$. An association of σ_B with v_G , however, is not pursued.)

In the model being considered here identical clouds are placed randomly in velocity space according to a Gaussian distribution given by

$$f(v_G/\sigma_G) \propto \exp - \frac{1}{2} \left(\frac{v_G}{\sigma_G} \right)^2 \quad (8)$$

where σ_G is the dispersion of the cloud distribution in velocity space. We loosely associate σ_G with the mass M and an emission-weighted radius R_G (e.g. the reverberation radius) giving $\sigma_G \approx \sqrt{2GM/R_G}$. Thus σ_G does not include the effect of magnetic broadening which must be added separately to each cloud.

We will predict the profile of the 1549-Å line of C IV. The surface emissivity of a cloud, $\epsilon(\text{C IV})$, is given by an analytical fit of C IV emission for an amalgam of BLR cloud densities as prescribed in Baldwin et al. (1995). The fit is given in Bottorff et al. (1997) and is reproduced here for convenience.

$$\log \epsilon(\text{C IV}) \propto [\log \Phi_{18}(\text{H})]^{0.67}. \quad (9)$$

Here $\Phi_{18}(\text{H}) = \Phi(\text{H})/10^{18}$ where $\Phi(\text{H})$ is the hydrogen-ionizing photon number flux in $\text{cm}^{-2} \text{s}^{-1}$. Following Netzer & Laor (1993) we assume that lines are suppressed with the onset of grain formation at $\Phi_{18}(\text{H}) = 1.0$ so we assign zero emissivity to clouds exposed to this flux or less. This is satisfied for

$$8.5 \times 10^{-4} R_{G,10}^2 / L_{45} \approx (v_G/\sigma_G)_{\text{cut}}^4 \quad (10)$$

where $R_{G,10}$ is the radius R_G , written in units of 10 light-days, L_{45}

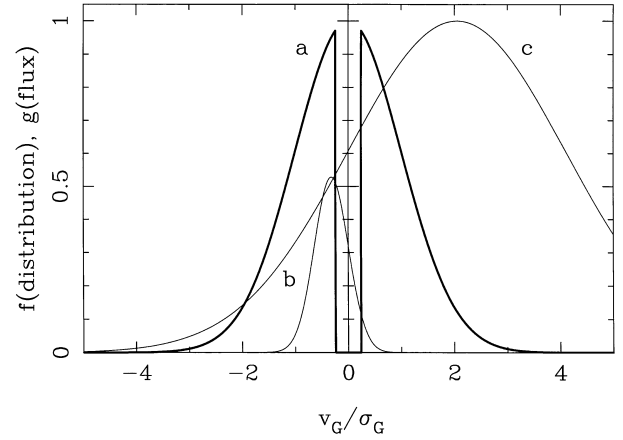


Figure 1. Plot of the distribution $f(v_G/\sigma_G)$ normalized to $f(0.0) = 1.0$ and including a $(v_G/\sigma_G)_{\text{cut}} = 0.24$ cut-off [(a), thick line]. Also shown is $g(-0.32, v_G/\sigma_G)$ and $g(2.05, v_G/\sigma_G)$ [(b) and (c) respectively, thin lines]. Both are normalized so that $g(2.05, 0.0) = 1.0$.

is the bolometric luminosity in units of $10^{45} \text{ erg s}^{-1}$ and $(v_G/\sigma_G)_{\text{cut}}$ is the value of $|v_G/\sigma_G|$ below which the emissivity is defined to be zero. We take $R_{G,10} \approx 1.0$ and $L_{45} \approx 0.27$ (values corresponding to the Seyfert 1 galaxy NGC 5548, Bottorff et al. 1997) so $(v_G/\sigma_G)_{\text{cut}} \approx 0.24$. For comparison, an example of a quasar is 3C 390.3 which has $R_{G,10} \approx 6.3$ and $L_{45} \approx 1.8$ (Wamsteker et al. 1997) giving $(v_G/\sigma_G)_{\text{cut}} \approx 0.43$. The cut-off in emissivity is equivalent to truncating the distribution $f(v_G/\sigma_G)$. The thick curve in Fig. 1 shows $f(v_G/\sigma_G)$ normalized to $f(0) = 1.0$ and truncated for $|v_G/\sigma_G| < 0.24$.

Our simulation used a total of 84 000 clouds, estimated from typical BLR cloud-column densities, particle densities and the size and covering fraction of the BLR. To simulate MHD wave broadening, each cloud was given a Gaussian line profile centred at a randomly selected value of v_i/σ_G and assigned a dispersion equal in magnitude to v_i/σ_G so as to be consistent with equation (7). The cloud line profile, $g(v_i/\sigma_G, v_G/\sigma_G)$, is thus

$$g\left(\frac{v_i}{\sigma_G}, \frac{v_G}{\sigma_G}\right) \propto \frac{\epsilon(\text{C IV})}{\sqrt{4\pi} \left(\frac{v_i}{\sigma_G}\right)^2} \exp - \frac{1}{2} \left(\frac{(v_G/\sigma_G) - (v_i/\sigma_G)}{v_i/\sigma_G} \right)^2. \quad (11)$$

A cloud with small $|v_i/\sigma_G|$ [but still larger than $(v_G/\sigma_G)_{\text{cut}}$], has a relatively narrow width and makes a smaller small-flux contribution to the total line profile as compared with clouds with larger $|v_i/\sigma_G|$. For comparison, Fig. 1 also shows two cloud profiles, namely $g(-0.32, v_G/\sigma_G)$ and $g(2.05, v_G/\sigma_G)$. Both have been normalized to $g(2.05, 0.0) = 1.0$. It is apparent in the figure that, individually, clouds with high $|v_i/\sigma_G|$ outshine those with low $|v_i/\sigma_G|$. For the two cloud profiles shown in Fig. 1 the larger $|v_i/\sigma_G|$ cloud is 10 times more luminous. On the other hand, there are many more low-velocity clouds than high-velocity clouds because of the distribution $f(v_G/\sigma_G)$. The resulting profile which is owing to the accumulation of all 84 000 clouds is shown in Fig. 2 though only 81 per cent of the clouds actually contribute to the line profile because of the cutoff. The profile represents the BLR contribution of an AGN emission line.

Analysis of this model shows that lowering the number of clouds to 300 has little effect on the line profile though it does

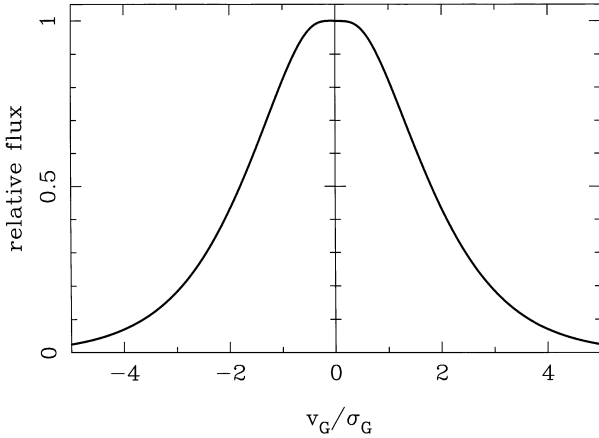


Figure 2. Simulated BLR portion of an emission line profile for our simple 1-D model. For this simulation 84 000 clouds were used with $(v_G/\sigma_G)_{\text{cut}} = 0.24$.

become somewhat less symmetric because of the sensitivity of the profile to large individual contributions from high-velocity clouds. The effect of MHD wave broadening is apparent when the FWHM of the profile in Fig. 2 is compared with the FWHM of $f(v_G/\sigma_G)$. The line profile is 1.6 times wider than $f(v_G/\sigma_G)$. The same model with 84 000 clouds but using $(v_G/\sigma_G)_{\text{cut}} = 0.43$ (e.g. parameters for 3C390.3) yields a similar profile to the one shown in Fig. 2. It is somewhat wider (the FWHM is 1.7 times larger than the FWHM of $f(v_G/\sigma_G)$) but has a flat plateau nearly twice as wide.

In the following section we interpret the above results in terms of current AGN research and make suggestions for future avenues of study.

2.2 Can the cloud nature be determined?

This simple model brings a whole series of issues to the study of AGN phenomena. Attempts to infer cloud numbers from broad line profiles need to include the possibility of MHD wave line broadening before making conclusions about whether BLR clouds are continuous or discrete. If individual clouds are sought, the search needs to be redirected away from the line wings and toward the line core since, by equation (4), the line broadening, σ_B , will be weaker at smaller values of v .

An alternative approach to AGN cloud counting could be to use a principle component-analysis fitting approach. The Gaussian basis functions used to fit a profile can be given widths proportional to their offset from zero systemic velocity. The minimum number of Gaussians required to find an acceptable fit to the line profiles will be an estimate of the minimum cloud number. Components may be tested in AGN that have had extensive spectral monitoring (e.g. NGC 5548, NGC 4151, 3C 390.3 and 3C273). A sequence of spectra, covering a time-span shorter than the BLR dynamical crossing time but longer than a characteristic continuum variability time-scale, can be fitted. If the component number and locations in the sequence do not significantly vary, then that would be evidence in favour of the components being actual clouds. The ensemble could be further tested against various kinematic models by tracking detected clouds over a few crossing times. There is already evidence to suggest that line profiles of clouds are a complex amalgam of emitters. Multiple components are often required to fit line profiles. For example, four or five components are required to fit

the H β line of Ark 120 (Korista 1992) and H β in NGC 5548 shows three seemingly independent time-variable components (Wanders & Peterson 1996). We note, for clarity however, that it is not suggested that the components presented in those papers necessarily represent actual clouds since the fitting algorithms are designed for efficiency and have no physical meaning. We do, however, wish to emphasize the potential for future reanalysis of available data.

With regard to magnetic broadening and long-term profile variability, consider the ‘shoulders’ of the H β line of NGC 5548 reported by Wanders & Peterson (1996). They note that shoulders ‘do not appear to move systematically in radial velocity but appear to come and go at approximately fixed wavelengths.’ In terms of our simple model this behaviour can be explained by the movement of a few relatively high-velocity clouds. Since both the emission and linewidth is large in these clouds we would expect that the wings vary on a time-scale of the order of the BLR crossing time, which they estimate to be ~ 1.6 yr. This is indeed the case. The line core in our model, however, is dominated by many dimmer clouds. Thus the profile core will be relatively stable since the addition or subtraction of a few clouds will not affect the overall shape of that segment of the line. In addition, the crossing time at a lower velocity will be longer than average. The net result is a stable line core with wings that occasionally balloon into shoulders. Shouldering may therefore indicate the movement of a few high-velocity extremely MHD broadened clouds. An observer might be able to track individual clouds by subtracting shouldered spectra from a mean spectrum or from a pre- or post-shoulder state of a line wing. Based on our modelling of the line profile for ~ 300 clouds and comparing it with the amplitude of the shouldering observed in NGC 5548 there may be only a few hundred clouds in this object (see also Wanders 1997).

Current virial mass estimates based on profile width will be too big. Energy equipartition of gravity with the magnetic wave energy results in an error of a factor of $\sim 1.6^2$ (~ 2.6) in the virial mass if the FWHM of the line is used. This is a consequence of equation (7) ($\sigma_B \approx v_G$). Line profiles are wide because of roughly equal contributions from the velocity field of the cloud ensemble and the linewidths of individual clouds. Additional non-kinematic mechanisms used to explain the extreme wings of broad-line profiles (e.g. electron scattering, Emmering et al. 1992; Bottorff et al. 1997), could also be at work though magnetic broadening may obviate the need for them to account for the wings of line profiles. The widths of clouds in the extreme wings guarantee overlap in one wing with the profiles of clouds in the other wing and the line core. The response of the extreme wings to short-term changes in the continuum (not to be confused with the long-term kinematic changes discussed above) will be smoothed. Thus, for short-term variability, because of rapid changes in the continuum, our model predicts a variable central part of the profile and a temporally smoothed response in the extreme wings.

An observer’s orientation with respect to the magnetic field will affect the observed profile if the field is coherent. The FWHM of a cloud should be wider in the plane of oscillation than if viewed along the magnetic field. In addition, cloud models need to be modified to include the effects of large non-dissipative internal motions on radiation transfer within a cloud.

Finally, dynamical mechanisms for initiating oscillations need to be investigated. Spatial wave amplitudes of

$$A \approx \lambda/2\pi, \quad (12)$$

where λ is the wavelength, are required to produce transverse

displacement velocities comparable with σ_B . Since the length of a cloud is $l \approx N_{24}/n_{10} \times 10^{14}$ cm, where N_{24} is the column density in units of 10^{24} cm $^{-2}$ and n_{10} is the cloud-particle density in units of 10^{10} cm $^{-3}$, the longest wavelength supported in a cloud is of the order $l \approx \lambda$. Using equation (7) gives the period of oscillation, T , which is bounded by

$$T \lesssim \frac{\lambda}{\sigma_B} \approx 3 \times 10^5 \frac{N_{24}}{n_{10}} \sqrt{\frac{R_{10}}{M_7}} \text{ s.} \quad (13)$$

Thus, T is about 4 d *or less* for fiducial values. We note that many continuum engines vary on a time-scale of this order so radiation pressure could be important. The importance of radiation pressure effects in static magnetic outflows is clearly demonstrated in Königl & Kartje (1994). Whether or not oscillations can be initiated by it, however, is still an open question.

3 CONCLUSIONS

Magnetic confinement and associated MHD wave broadening have broad ramifications.

(i) Energy equipartition between non-dissipative waves ($1/2\rho\sigma_B^2$) and the magnetic field ($B^2/8\pi$) seems to be an inevitable consequence of magnetically confined gas. Line broadening is expected everywhere magnetic fields are found. In cases where there is also energy equipartition with gravity, the effects of magnetic line broadening will be extreme.

(ii) The spectrum emitted by clouds subject to MHD wave broadening needs to be reevaluated since the local velocity field will be highly supersonic, not thermal as previously assumed. This will have fundamental effects on the spectrum since line trapping will be far less severe and continuum pumping far more important (Ferland 1999).

(iii) Virial mass estimates will be too large by a factor ~ 2 if the magnetic field is in energy equipartition with gravity.

(iv) The smallest resolved component in a line may be considerably broader than its thermal width. If a component is part of an ordered flow, then its width can rival that of the flow if the magnetic field is in energy equipartition with gravity. This has important implications for current attempts to detect and count individual cloud elements.

(v) Line profiles broadened by a magnetic field will be more symmetric than expected by predictions of a kinematic model that uses thermal broadening only. Thus the parameters describing the shape of a model line profile may need to be changed considerably once correct radiative transfer is applied.

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